Summary of Research on the Nuclear Light Bulb Reactor[1]

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The objectives of this paper are to outline the overall nuclear light bulb research program and to summarize the progress that has been made in the major areas. In addition, those factors that have limited progress to date will be discussed; these are the research areas that are receiving major emphasis at the present time. There are five other detailed papers on the nuclear light bulb in the present symposium proceedings. Further details are presented in references 1 through 6.

ENGINE CONCEPT

Figure 1 is a schematic of a unit cell of a nuclear light bulb engine. Gaseous nuclear fuel (uranium-233) is contained in a vortex flow in the central region of the cavity. Hydrogen propellant, seeded with tungsten particles to increase its opacity, flows axially in an annular propellant duct. A thin, internally cooled, fused silica transparent wall is located between the fuel and propellant. The energy from the fissioning fuel is transmitted by thermal radiation through the wall to the propellant. The fuel is kept away from the wall by neon buffer gas that is injected from the wall to drive the vortex. Fuel is injected through the end wall as a liquid or as particles with a carrier gas. Flow consisting of buffer gas, fuel, and fission products is withdrawn at one or both end walls and enters a fuel recycle system.

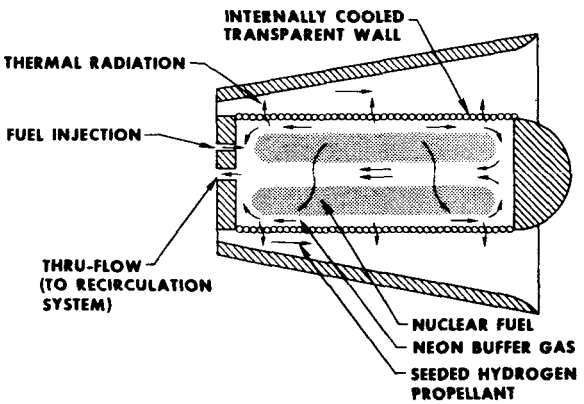

FIGURE 1.—*Concept of nuclear light bulb engine.*

In the full-scale engine, this unit cavity would be about 6 ft long, and the diameter of the transparent wall would be about 16 in. Seven unit cavities would be clustered in a hexagonal array with an internal moderator.

The major performance characteristics of the reference full-scale engine design are: Power, 4600 MW; specific impulse, 1870 sec; thrust, 92 000 lb; weight, 70 000 lb; and pressure, 500 atm. The important parameters to note are the specific impulse (1800 to 1900 sec) and the engine weight and thrust levels (on the order of 100 000 lb). This reference engine would operate at 500 atm and the total radiant heat flux from the fuel would correspond to that of a blackbody at 15 000° R. It is the standard engine used for planning the nuclear light bulb research program.

NUCLEAR LIGHT BULB RESEARCH PROGRAM

Some research has been conducted on all aspects of the engine concept, either as part of the NASA program or under the United Aircraft internal research program. The basic approach, however, has been to single out and concentrate on those funda-

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mental problem areas necessary for determining the feasibility of the concept.

The current nuclear light bulb research program can be outlined as follows:

(1) Simulation of thermal environment:
  (*a*) Radiant energy source research
  (*b*) Transparent-wall model research
  (*c*) Propellant heating research
  (*d*) Supporting research
(2) Engine dynamics and startup analyses
(3) Radiation heat transfer analyses
(4) Optical absorption in fused silica

Most of the current research effort is in these four main areas. The major effort is concerned with simulating the thermal environment in the engine. The ultimate objective is to conduct a nonnuclear experiment which demonstrates the principle of operation of the engine while as many of the important factors as possible are simulated. As stated in the outline, the four areas of research involved are: Development of a radiofrequency (rf) plasma radiant energy source, development and testing of transparent-wall models, radiant heating of propellant streams seeded with particles, and supporting vortex fluid mechanics and rf plasma studies. The most important features of this work are discussed in the next section.

SIMULATION OF THERMAL ENVIRONMENT

The basic components used in the rf experiments are shown schematically in figure 2. A pair of

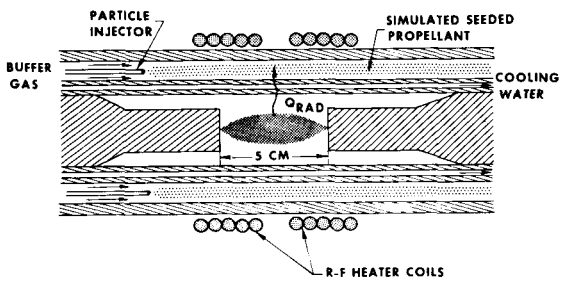

FIGURE 2.—*Geometry of radiant energy source.*

cylindrical, copper, water-cooled end walls are located along the centerline of the assembly. The faces of these end walls are 5 cm apart. Argon is injected from the end walls or from the peripheral wall (injection geometry not shown) to form a vortex. Flow is withdrawn at through-flow ports at the centers of the end walls. The plasma shape is similar to that shown in figure 2; it is from 0.6 to about 0.9 in. in diameter and is approximately ellipsoidal in shape. The diameter, shape, and stability of the plasma are strongly dependent upon three parameters: The argon mass flow, the pressure in the test chamber, and the power deposited in the plasma by the rf system.

Fused silica models of the transparent walls are located concentric with, and adjacent to, the plasma (fig. 2). The simulated propellant stream (argon seeded with carbon particles in experiments to date) is injected through the annulus outside of the transparent-wall model. There are unseeded buffer streams on the inside and outside of the seeded stream to help keep the carbon particles off the transparent-wall model and outer wall. A larger diameter fused silica tube forms a pressure vessel, and the 3-in.-i.d. rf work coils surround this tube. Further details are given in reference 2.

Three types of tests are conducted using the components shown in figure 2. Radiant energy source tests are conducted without the transparent-wall model and without the propellant stream. Transparent-wall model tests are conducted with this wall but without the propellant stream. Finally, for propellant heating tests, the complete geometry is used.

Radiant Energy Source Tests

Figure 3 summarizes the results of the radiant energy source tests. The left-hand ordinate indicates the radiant heat flux at the edge of the plasma and the right-hand ordinate indicates the corresponding equivalent (same total flux) blackbody radiating temperature. The abscissa indicates the power deposited in the plasma. The major result is that a flux of 36.7 kW/in.^{2}, which corresponds to a blackbody temperature of 10 200° R, has been attained. This is less than the 15 000° R of the reference engine, but it is nevertheless a useful flux level. To increase the flux further it is necessary to increase the power deposited in the plasma and also the chamber pressure; the highest values attained to date are 216 kW deposited (of which 156 kW were radiated) and 16 atm. Details of these tests are given in reference 2. The vacuum capacitor cooling

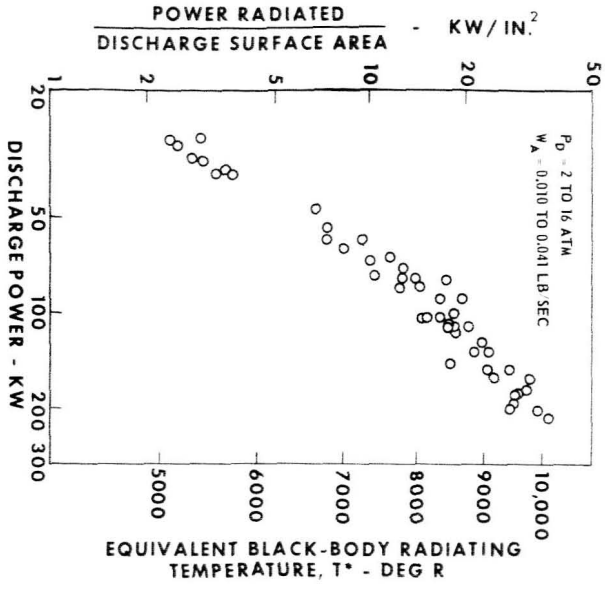
POWER RADIATED
DISCHARGE SURFACE AREA - KW/IN.²
DISCHARGE POWER - KW
EQUIVALENT BLACK-BODY RADIATING TEMPERATURE, T* - DEG R
P_D = 2 TO 16 ATM
W_A = 0.010 TO 0.041 LB SEC

FIGURE 3.—*Performance of radiant energy source.*

capability in the rf resonator has been increased to allow tests in which the flux is increased by about 25 percent. The emphasis has now shifted, however, from attempts at major additional increases to efforts in the transparent-wall model and propellant-heating areas.

Transparent-Wall Model Tests

A photograph of a transparent-wall model is shown in figure 4. It consists of 39 fused silica tubes each having an i.d. of 0.050 in. and an o.d. of 0.060 in.; thus, the wall thickness of the tubes is 0.005 in., the thickness required in the reference engine design. The diameter of the circle of tubes is 1.26 in. The tubes are potted into the end manifolds using silicone rubber. There are three copper injectors from which argon is injected through a series of small holes to drive the vortex. From experiments with a variety of fabrication methods, the point has been reached where models such as this can be made routinely using the thin 0.005-in. tubing. Consideration is now being given to models using even thinner tubing.

In tests with these models around the rf radiant energy source, the model has been successfully cooled at the full-scale heat flux (ref. 2). However, unlike with the full-scale reference engine, most of the heat was deposited by convection and conduction, rather than by radiation. This was primarily due to relatively poor flow conditions in the vortex chamber; the flow was turbulent, so the diameter of the plasma was large and the plasma was close to the wall. As the power was increased, the uncooled copper vortex injectors buckled in such a manner that the injection angles varied widely and, in some tests, adjacent fused silica tubes began to flutter. In addition, the tubes were far enough apart that there were substantial flows between the vortex region and the surrounding annulus. Since the most recent series of model tests with rf plasma during the summer of 1969, several sets of copper injectors with water cooling have been built and bench tested. Also, the tubes are now potted differently so that the intertube gaps have been essentially eliminated. These new models have been tested using water instead of argon in the vortex; by injecting fluorescent dye, the flow patterns have been observed to be improved. Therefore, it is expected that the flow will also be improved when testing is resumed with rf plasmas.

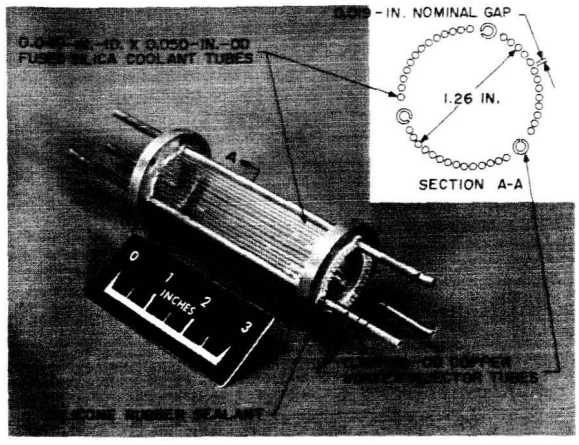

FIGURE 4.—*Photograph of transparent-wall model.*

Propellant Heating Experiments

Propellant heating experiments were initiated in the spring of 1969 (ref. 2). These first attempts at UARL to use thermal radiation to heat argon seeded with carbon particles did not result in large temperature rises; the maximum temperature rise achieved was only about 200° F. It was determined, however, that there were three reasons for this. First, because of poor vortex flow conditions within

the transparent-wall model, the plasma power was limited to conditions with less than about 3 kW of radiation. Second, the mass attenuation parameter of the particle-seeded stream (a measure of the amount of energy absorbed) was less than about 2000 cm^2/g. In other experiments at UARL and elsewhere, where the ducting between the particle feeder and the test section was not so complicated, values of 5000 to 10 000 cm^2/g (and even higher) have been obtained. This indicates that, in the present experiments, the particles were not sufficiently deagglomerated in the ducting between the particle feeder and the propellant duct. The third reason was the occurrence of coating of the particles on the transparent-wall model. Recent results have shown that thicker buffer layers and the use of a foam material at the inlet of the propellant duct to reduce turbulence should greatly reduce the amount of wall coating.

As a result of the initial experience, major emphasis is now placed on these three areas individually. It is estimated conservatively that an improvement by a factor of at least 20 in the propellant temperature rise should result from these recent efforts. Thus, a temperature rise of at least 4000° R, and probably more, should be possible in the near future.

Supporting Research

The supporting research noted earlier consists primarily of unheated and rf-heated two-component gas vortex tests (ref. 3). These tests are directed toward attainment of a high partial pressure of simulated fuel in the cavity with no fuel near the transparent wall. To date, simulated-fuel partial pressures well in excess of that required for the engine have been obtained (ratios of fuel partial pressure to total cavity pressure as high as 0.44 were obtained, compared with the 0.25 required). In these unheated tests, the radial distribution of simulated fuel has been similar to that desired for the engine except that a small amount of fuel was present near the outer wall. The results of the tests with rf heating have shown, as expected, that the presence of a radial gradient of temperature helps reduce turbulence near the wall and thereby decreases the amount of fuel present in the vicinity of the wall.

ENGINE DYNAMICS AND STARTUP ANALYSES

In the second portion of the nuclear light bulb research program the major effort has been to construct a UNIVAC 1108 digital computer simulation of the dynamics of the engine. The simulation includes all of the coolant loops and their associated time constants, the hydrogen turbopump dynamics, the fuel injection and recycle system, the nuclear kinetics, etc. The major conclusion to date from these studies is that the basic uncontrolled engine has neutrally stable or slightly damped characteristics. Moreover, control of the fuel flow rate appears to offer a very satisfactory method for obtaining good closed-loop control of the engine (ref. 5).

Analyses of possible startup procedures have also been made (ref. 5) using a simplified analytical model of the basic engine. Linear power ramps were used and the general engine response, auxiliary power requirements, and thermal stress levels were investigated. The results obtained to date indicate that no major problems exist with engine control or with thermal stresses during startup, even during ramps as short as 6 sec.

RADIATION HEAT TRANSFER

The primary current effort in the area of radiation heat transfer involves calculations of the thermal radiation spectrum incident upon the transparent wall. Recent calculations of the spectrum emanating from the fuel region in the reference engine have indicated that a substantial amount of energy is radiated in the ultraviolet portion of the spectrum. Below 0.2 μ, the calculated spectrum has about 4 to 5 times as much energy as does a blackbody spectrum for a 15 000° R source. Consideration is being given to adding small amounts of different seed gases—particularly oxygen—in the buffer gas and fuel regions to prevent much of this ultraviolet energy from reaching the wall (ref. 4).

OPTICAL ABSORPTION IN FUSED SILICA

The final research area noted is optical absorption in fused silica. Basically, there are several phenomena occurring as the nuclear radiation (par-

ticularly neutrons and gamma rays) passes through the transparent wall. This radiation tends to discolor the wall, thereby locally decreasing the transmissivity to thermal radiation. However, there are two alleviating processes: If the wall is maintained at a high enough temperature, thermal annealing of the coloration takes place; also, under intense illumination, optical or photon bleaching takes place to remove the radiation-induced opacity.

Several experimental programs have been conducted in which measurements have been made of the transmissivity of high-quality fused silica samples before, during, and after irradiation, at room temperature, and at elevated temperatures (ref. 6). The major effect of the radiation is to induce an absorption band in the fused silica centered at about 0.21 μ. On the basis of recent tests at elevated temperatures, and with the beneficial effect of optical bleaching omitted, it is estimated that the wall coloration and the resulting increase in the absorption of thermal radiation would require a decrease in the thickness of the transparent-wall tubing from 0.005 in. to about 0.003 or 0.004 in. In the near future, experiments will be conducted to determine the effectiveness of optical bleaching in removing induced coloration in the fused silica.

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DISCUSSION

Anonymous: Is the spectral distribution of your rf sources the same as that of a blackbody radiator?

Clark: No. The spectral distribution of the rf source contains many lines. However, we define a blackbody temperature which is equivalent to the total heat flux.

Anonymous: Isn't spectral distribution very important for your wall transmission? Thus, can you really simulate the radiation of uranium?

Clark: At the present time we do not know much about the uv radiation reaching the wall. It depends upon how much is absorbed by the oxygen.

Ragsdale: What are the chances that a materials research program would suggest another wall material?

Clark: Other materials which we have considered are alumina, which is Al_2O_3, and single-crystal beryllium oxide drawn into tubes. At the present time we think only the BeO would be suitable. This is not available at the present time so we are trying silicon.

Bostick: What gases were used in your experiment and how did you initiate the discharge?

Clark: In these experiments argon was used and we started the discharge by using a retracting electrode that comes in from the end walls. Since we were interested in high pressures, we started at 2 or 3 atm. In other experiments, which Arthur Mensing will discuss, we mixed argon with xenon. The objective is to probe the plasma by spectroscopy. We want to see how much of the xenon, which simulates the fuel component, will actually stay in the plasma region.

Monsler: What pressure difference can such walls withstand?

Clark: There are two pressure drops that one has to be concerned with. The drop connected with the need to flow coolant through the transparent tubing in order to remove the heat that is deposited in the wall doesn't seem to be a problem. The pressure difference between the region inside the wall and the outside is a more serious problem. We expect a pressure drop of approximately $\frac{2}{3}$ atm across the wall. A good pressure control system is needed.